UNIVERSITAT ROVIRA I VIRGILI

Compact Modeling of Organic and Oxide TFTs

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Goal

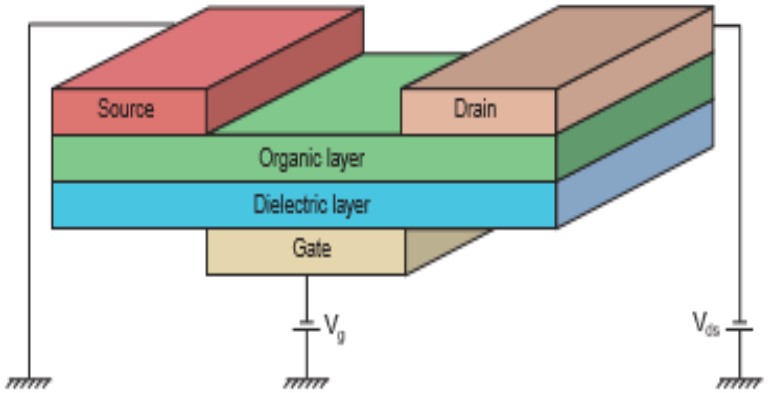
- Present compact models and parameter extraction methods for organic TFTs (OTFTs) and IGZO TFTs

- Analyze the temperature dependence of key parameters from 150K to 350K

Outline

- Introduction
- Parameter Extraction and Drain Current Model for OTFTs and IGZO TFTs
- Results
- Conclusion

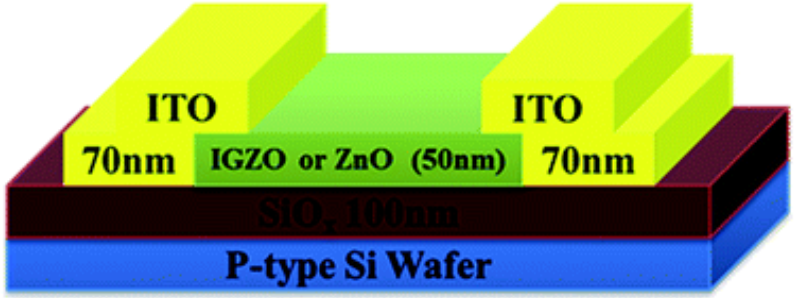
Organic Thin Film Transistor (OTFT)



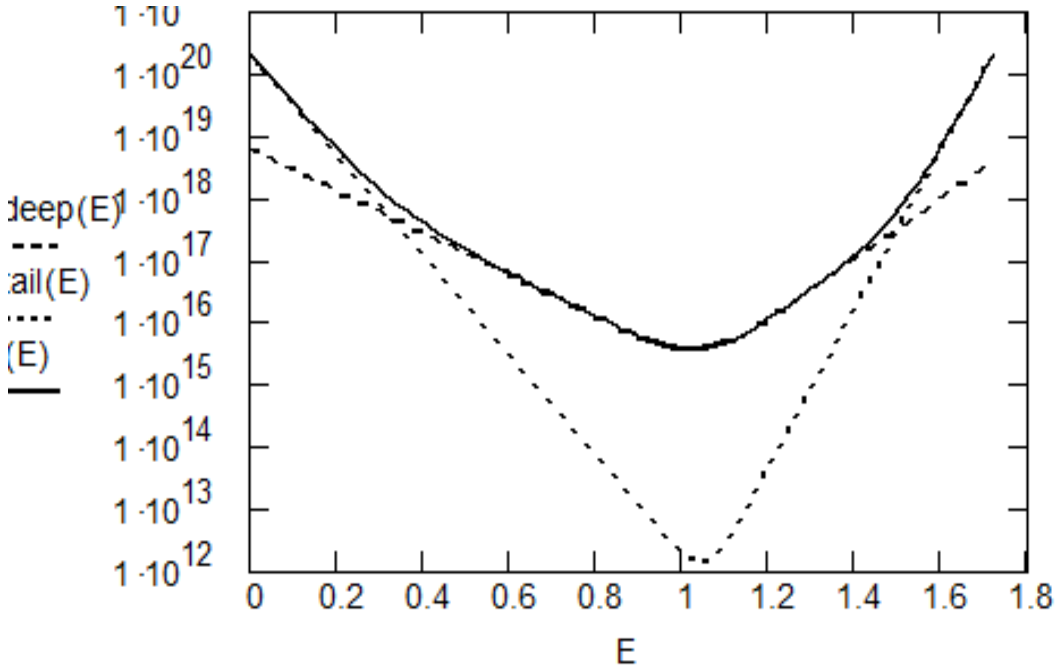
- MAIN FEATURES OF OTFTS:
  - Metal- insulator-semiconductor structure
  - Easy manufacturing
  - Flexible and printed materials
  - High sensitivity

IGZO TFTs

- MAIN FEATURES OF IGZO devices:
- Indium – Gallium – Zinc- Oxide semiconductor
- Metal-insulator-semiconductor structure
- Easy manufacturing
- Compatible with flexible substrates
- Low leakage current
- Higher Mobility than OTFTs
- Already commercial applications in displays



Introduction



Introduction

- Main modeling assumptions:
- The targeted IGZO TFTs are n-channel. The targeted OTFTs are p-channel, but for convenience model equations use positive voltages and positive current, as in n-channel devices
  - A single exponential DOS in OTFTs
  - Deep states density negligible in IGZO TFTs
    - Single exponential acceptor tail states in IGZO TFTs

Introduction

- 1D Poisson's equation has no analytical solution if a Gaussian DOS is used for OTFTs
- An analytical solution is possible assuming an exponential DOS, as in a-Si:H TFTs

$$DOS_{gauss} = \frac{N_V}{\sqrt{2\pi}\sigma}\exp\left(-\left(\frac{\varepsilon-\varepsilon_0}{\sqrt{2\pi}\sigma}\right)^2\right)$$

$$DOS_{\exp} = \frac{N_t}{kT_0}\exp\left(\frac{\varepsilon}{kT_0}\right)$$

$$\frac{d^2\psi}{dy^2} = N_t\delta_0 e^{\frac{q\psi}{kT_0}},$$

Introduction

In [*] it was shown that for OTFTs, it can be considered that $Q_{loc} >> Q_{free}$ in above threshold regime and Poisson´s equation has an analytical solution for the electric field and the induced sheet charge in the channel.
The DOS is represented as:

$$g_d(E) = g_{do} \exp\left(-\frac{(E - Ev)}{k_b To}\right)$$

[*] M. Estrada et al., Solid State Electronics, 52 (2008) 787.

Introduction

- Transport in OTFTs is due to variable range hopping of carriers between localized states
- Transport in IGZO TFTs includes both free and localized carriers

- OTFT model in:
- M. Estrada et al., *Solid State Electronics*, 52 (2008) 787
- C. H. Kim et al., *IEEE T-ED*, vol. 60, no. 3, pp. 1136-1141, 2013
- H. Cortés-Ordóñez et al., *IEEE T-ED*, vol. 66, no. 1, 2019

- IGZO TFT model in:
- O. Moldovan et al., *Solid-State Electronics*, vol. 126, pp. 81-86, 2016
- Y. Hernández-Barrios et al., *Solid-State Electronics*, vol. 149, pp. 32-37, 2018

Above threshold I_D model for OTFTs and IGZO TFTs

- Power-law field effect mobility dependence on $V_{GS} - V_T$ Same shape as for a-Si:H TFT:

$$\mu_{FET} = \frac{\mu_O}{V_{AA}^{\gamma}} \cdot (V_{GS} - V_T)^{\gamma}$$

- Drain current model above threshold regime:

$$I_{DS} = \frac{W}{L} \cdot C_i \cdot \mu_{FET} \cdot \frac{(V_{GS} - V_T) \cdot V_{DS} \cdot (1 + \lambda \cdot V_{DS})}{\left[1 + R \cdot \frac{W}{L} \cdot C_i \cdot \mu_{FET} \cdot (V_{GS} - V_T)\right] \cdot \left[1 + \left[\frac{V_{DS}}{\alpha_S \cdot (V_{GS} - V_T)}\right]^m\right]^{\frac{1}{m}}}$$

C_i, gate capacitance.

α_S, Saturation Modulation parameter.

λ, Variation of conductance with V_{DS} (channel length modulation)

OTFT above-threshold model

The expression of mobility obtained is:

$$\mu_{FET} = \left[\mu_o \cdot P'(T,To) \cdot \frac{C_i^{\left(\frac{2To}{T}-2\right)}}{(\varepsilon_S)^{\left(\frac{To}{T}-1\right)}} \right] \cdot \left(V_{GS} - V_{FB}\right)^{\left[\frac{2To}{T}-2\right]}$$

$$\mu_{FET} = \left[\frac{\mu_o}{V_{aa}^{\gamma}} \right] (V_{GS} - V_T)^{\gamma}$$

where:

$$P'(T,To) = \frac{q \cdot k_b T \cdot N_V \cdot \exp\left[-\frac{E_{Fo} - E_V}{k_b T} \right]}{\left[\pi q \cdot k_b T \cdot g_{do} \cdot \exp\left(-\frac{E_{Fo} - E_V}{k_b To} \right) \right]^{\frac{To}{T}}} \cdot \left[\frac{\sin(\pi T / To)}{2 k_b To} \right]^{\frac{To}{T}}$$

$$\frac{\mu_o}{(V_{aa})^{\gamma}} = \mu_o P'(T,To) \cdot \frac{C_i^{\left(\frac{2To}{T}-2\right)}}{\cdot (\varepsilon_S)^{\left(\frac{To}{T}-1\right)}}$$

and

$$\gamma = \frac{2To}{T} - 2$$

Above threshold regime

- Saturation Voltage:

$$V_{Dsat} = \alpha_s (V_{GS} - V_T)$$

- Above threshold regime :

$$H(V_{GS}) = \frac{\int_0^{V_{GS}} I_{DS}(x)dx}{I_{DS}(V_{GS})}$$

$$H_1(V_{GS}) = \frac{1}{2+\gamma}(V_{GS} - V_T)$$

- Parameter extraction

- ***STEP 1:***

$$\gamma = \frac{1}{slope} - 2 \qquad V_T = \frac{inter}{slope}$$

- ***STEP 2:*** $\Rightarrow$ $I_{DS}^{\frac{1}{1+\gamma}}$ vs $(V_{GS} - V_T)$

$$V_{aa} = \left[\frac{\frac{W}{L}\mu_0 C_i V_{GS}}{Sl^{1+\gamma}}\right]^{\frac{1}{\gamma}}$$

Sl, $I_{DS}^{\frac{1}{1+\gamma}}$ vs $(V_{GS} - V_T)$ slope

Above threshold regime…

- STEP 3: $\Rightarrow$ $I_{Dsat}^{\frac{1}{2+\gamma}}$ vs $(V_{GS} - V_T)$

$$\alpha_S = \frac{Ss^{2+\gamma} V_{aa}^{\gamma} \sqrt{2}}{\frac{W}{L} C_i \mu_O}$$

- STEP 4:

$$m = \frac{\log 2}{\log\left[\frac{\frac{W}{L}\cdot C_i \cdot \left(\frac{\mu_o}{V_{AA}^{\gamma}}\right)\cdot \alpha_S \cdot \left(V_{DSsat1}\right)^{2+\gamma}}{I_{DSsat1}(V_{DSsat1})\cdot\left[1+R\frac{W}{L}\cdot C_i \cdot \left(\frac{\mu_o}{V_{AA}^{\gamma}}\right)\cdot\left(\frac{V_{Dsat1}}{\alpha_S}\right)^{1+\gamma}\right]}\right]}$$

Above threshold regime…

- STEP 5:

$$\lambda = \frac{\left[\frac{I_{DS2}}{V_{DS2}^2}\right]\cdot\left[1+R\frac{W}{L}\cdot C_i\cdot\left(\frac{\mu_o}{V_{AA}^{\gamma}}\right)\cdot\left(V_{GS1}-V_T\right)^{1+\gamma}\right]\cdot\left[1+\left(\frac{V_{DS2}}{\alpha_s\cdot\left(V_{GS1}-V_T\right)}\right)^{m}\right]^{\frac{1}{m}}}{\frac{W}{L}\cdot C_i\cdot\left(\frac{\mu_o}{V_{AA}^{\gamma}}\right)\cdot\left(V_{GS1}-V_T\right)^{1+\gamma}} - \frac{1}{V_{DS2}}$$

- STEP 6:

$$R = \frac{V_{DS1}}{I_{DSlin}\left(V_{GS\max}\right)} - \frac{1}{\left(\frac{W}{L}\right)\cdot C_i\cdot\mu_{FET}\cdot\left(V_{GS\max}-V_T\right)}$$

Non-linear contacts at drain and source

- At low temperatures, non-linear contact resistance effects (due to the Schottky barrier contact) may be relevant
- In this case, part of the applied voltage will fall across the non-linear contact, so the following expression can be written:

$$V_{DSext} = V_{DS} + V_{diode} = \frac{I_{DS}}{G(V_{GS}, V_{DS})} + n \cdot \frac{k \cdot T}{q} \cdot \log\left(\frac{I_{DS}}{I_{do}}\right)$$

Non-linear contacts at source and drain

Extraction of non-ohmic contact parameters:

- Select an output characteristic with $V_{GS}=V_{GS2}$, where the non-ohmic contact effect is clearly seen.
- Plot the curve $\log(I_{DS})$ vs. V_{DSext} and determine the slope, P_{diode}, and the intercept, *InterD*, of this curve near the origin.
- Calculate n and I_{do} as:

$$n = \frac{\log e}{P_{diode} \cdot \frac{k \cdot T}{q}}$$

$$I_{do} = 10^{InterD}$$

Non-linear contacts at source and drain

The non-linear resistance can be expressed as:

$$R_c = R_{co}\exp(-\eta V_{DS}) = \left[\frac{nkT}{q}\left(\frac{\lg(I_{DS}(V_{GS\max}))}{I_{do}}{I_{DS}(V_{GS\max}}\right)\right]\cdot\exp(-\frac{q}{nkT}V_{DS})$$

and the total contact resistance is equal to: $R_t = R + R_c$

Where R is the already extracted value of the series resistance, mostly due to the current path across the semiconductor layer in TGBC TFTs.

If the non-linear contact is not present, consider R_{co}=0.

R_t is now to be substituted in the expression for I_{DS} instead of R.

Subthreshold regime

- Subthreshold regime:

$$I_{DSb} = I_{DSo} \cdot \exp\left(-2.3\frac{(V_{GS} - V_T)}{S}\right)$$

- Parameter extraction
  - STEP 1:

$$S = \frac{2{,}3}{Slope(I_{Dst})}\frac{V}{Decade}$$

  - STEP 2:

$$I_{DSo} = e^{(Inter(I_D) + \frac{2{,}3V_T}{S})}$$

Complete Drain Current Model

- Full model of the drain current:

$$I_{DS} = |I_{DSa}| \cdot \left[\frac{1+\tanh[V_{GS} - (V_T + DV)\cdot Q]}{2}\right] + |I_{DSb} + I_o| \cdot \left[\frac{1-\tanh[V_{GS} - (V_T + DV)\cdot Q]}{2}\right]$$

- Parameters

$$DV = (V_{aa}^{\gamma} I_{DSO} \frac{L}{W C_i V_{D1}})^{\frac{1}{1+\gamma}}$$

$$Q \rightarrow V^{-1}$$

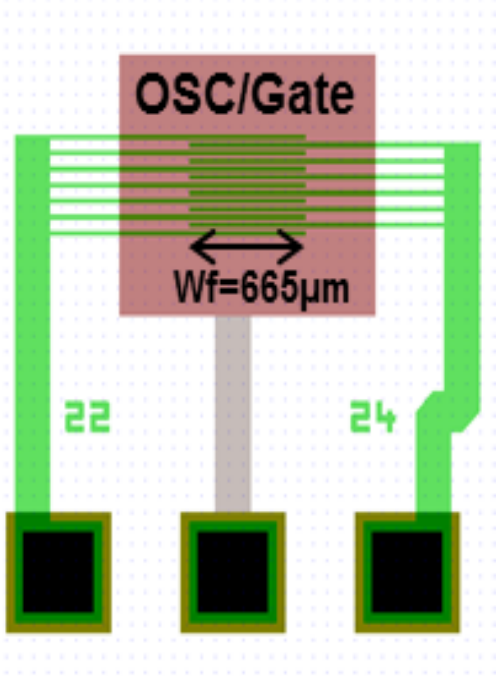
OTFT under study (first technology)

- Features of the device under analysis:
- Polymeric p-Type OFTF
- Top gate bottom multifingers
- $L = 20\ \mu m$
- $W = 7890\ \mu m$
- Dielectric

$$d_i = 700\ nm \qquad \varepsilon_{ir} \cong 2$$

- Semiconductor

$$d_s = 40\ nm \qquad \varepsilon_{sr} \cong 4$$



Characteristics of the study

- Transfer characteristics

$$V_G = 10V\ to\ -30V \qquad V_D = \begin{cases} V_{D_{lin}} = -1V \\ V_{D_{sat}} = -30V \end{cases}$$

- Output characteristics

$$V_D = 1V\ to\ -10V \qquad V_G = \begin{cases} V_{G1} = -10V \\ V_{G2} = -20V \\ V_{G3} = -30V \end{cases}$$

- Temperatures

$$T = 150K\ to\ 300K$$

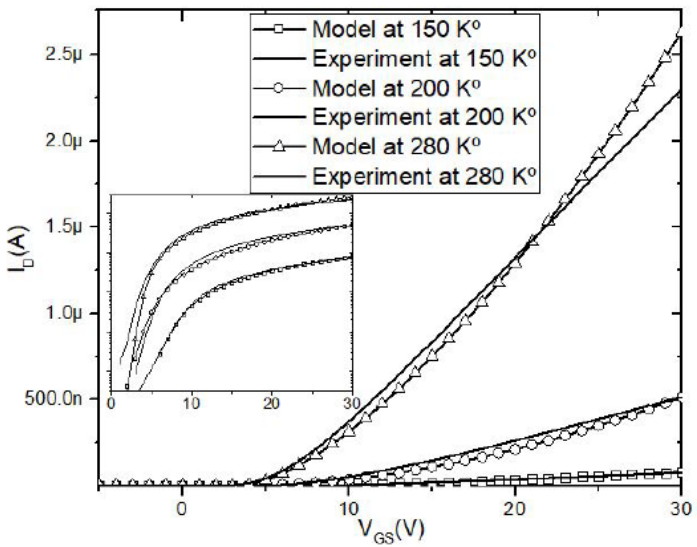
Results: DC characteristics

I_D at different temperatures

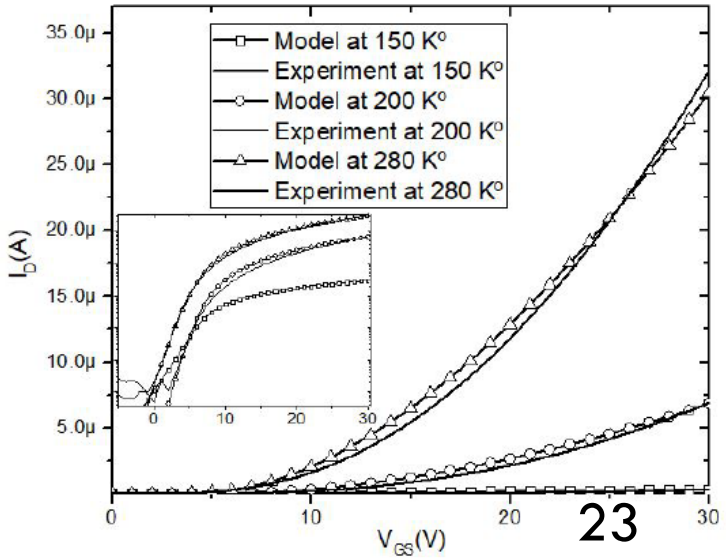
$$I_{DSb} = I_{DSo} \cdot \exp\left(-2.3\frac{(V_{GS} - V_T)}{S}\right)$$

$$I_{DS} = \frac{W}{L}\cdot C_i \cdot \mu_{FET} \cdot \frac{(V_{GS} - V_T)\cdot V_{DS}\cdot(1+\lambda\cdot V_{DS})}{\left[1+R\cdot\frac{W}{L}\cdot C_i\cdot\mu_{FET}\cdot(V_{GS}-V_T)\right]\cdot\left[1+\left[\frac{V_{DS}}{\alpha_S\cdot(V_{GS}-V_T)}\right]^m\right]^{\frac{1}{m}}}$$

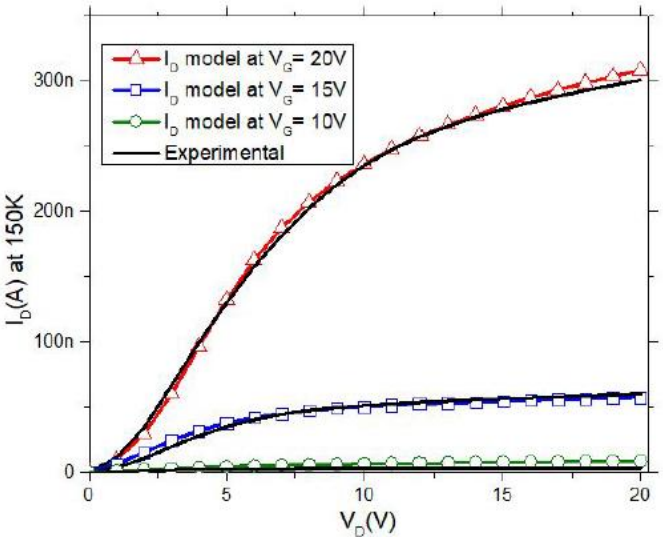
Linear regime $V_D = 1\ V$

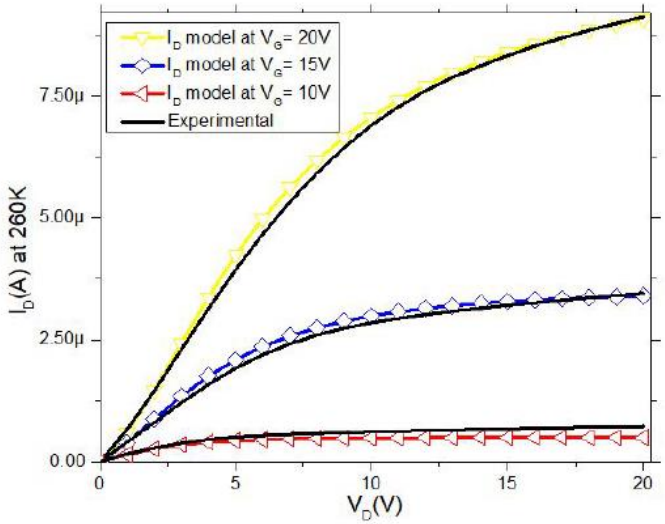


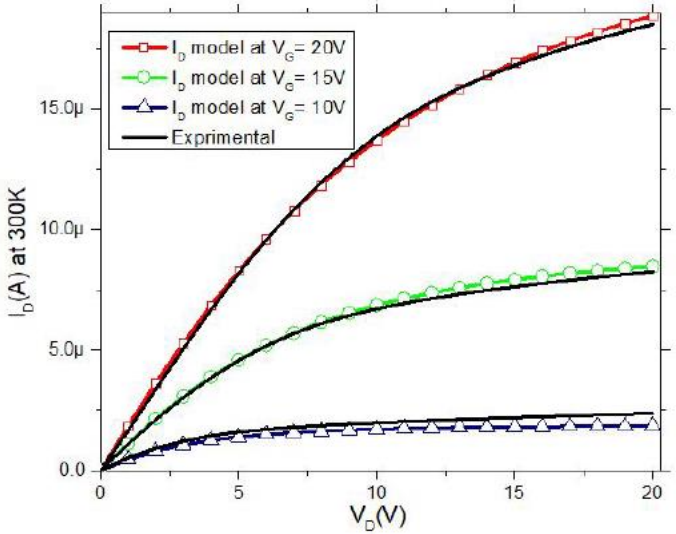
Saturation regime $V_D = 30\ V$



Results: DC characteristics

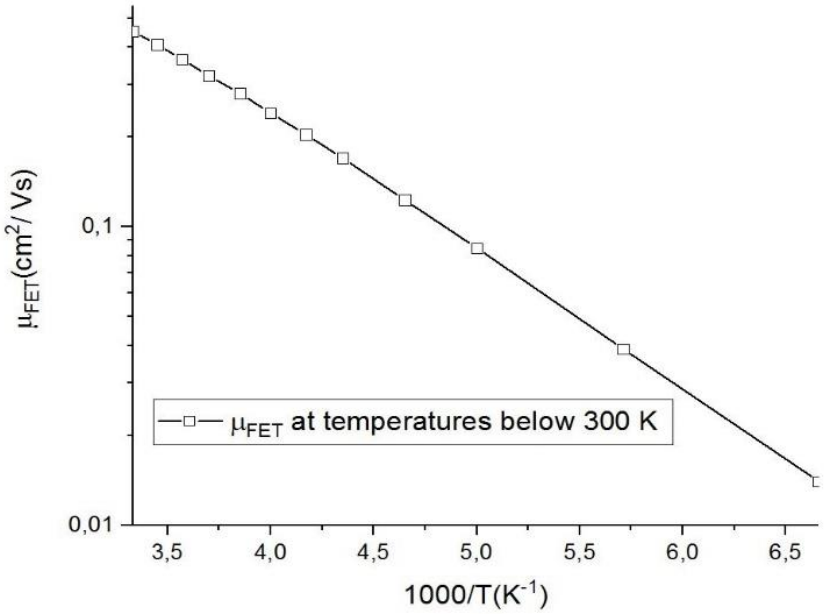


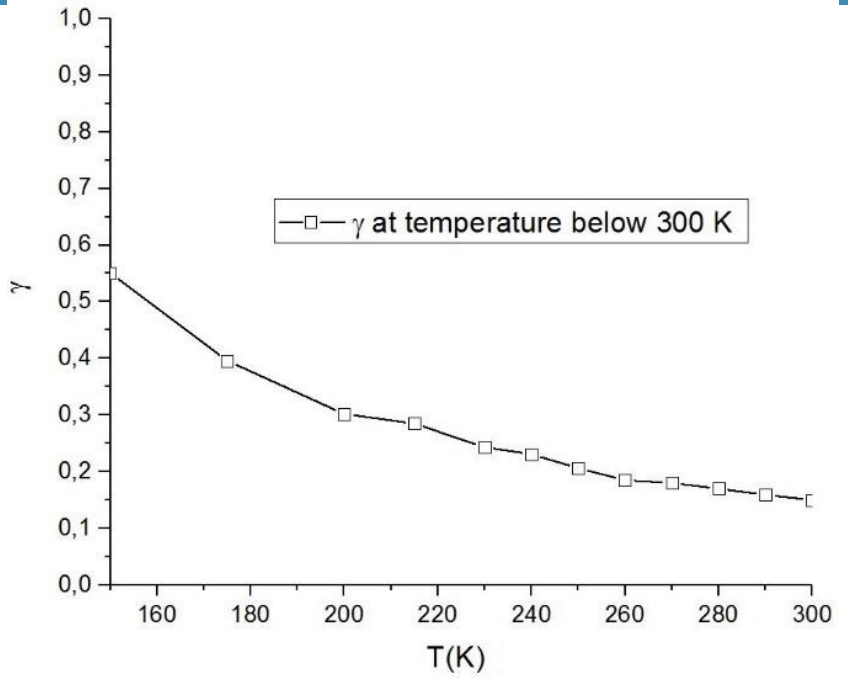




Results: Parameters extracted

$\gamma = 0\ to\ 1\ \ in\ OTFTs$





$$\mu_{FET} = \frac{\mu_O}{V_{AA}^{\gamma}} \cdot (V_{GS} - V_T)^{\gamma}$$

Field effect Mobility(30V)

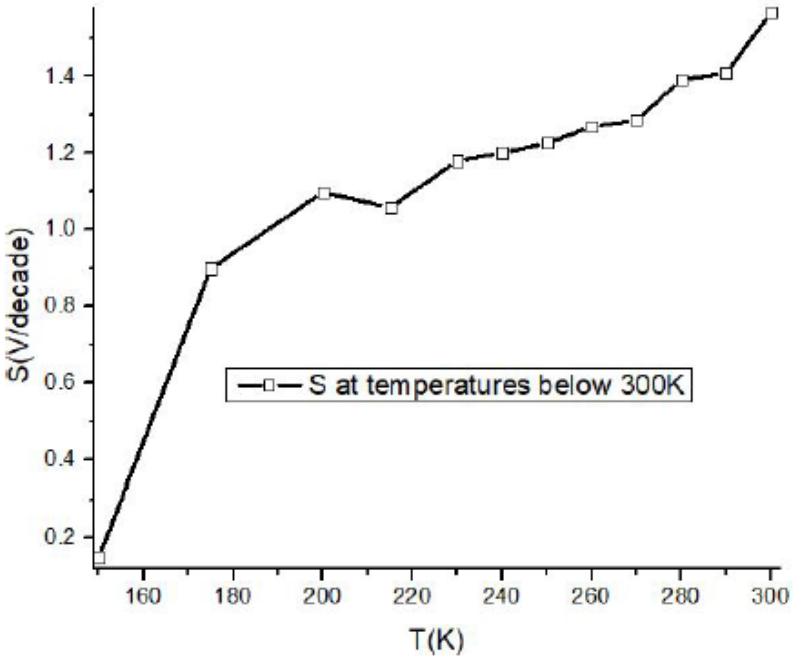
Results: Parameters extracted

	150K	215K	260K	280K	300K
γ	0.551	0285	0.185	0.17	0.15
$S[V/decade]$	0.149	1.058	1.269	1.392	1.567
$\mu_{FET}[cm^2/Vs]$	0.14	0.123	0.28	0.364	0.452
$V_T[V]$	6.05	5.28	4.76	4.45	4.25
$T_0[K]$	191	246	284	304	322
$g_{do}[cm^{-3}][10^{18}]$	3.493	1.913	1.444	1.331	1.227
$D_{it}[\frac{cm^{-2}}{eV}]$	=	=	$1.5968x10^{10}$	=	=

Results: Parameters extracted

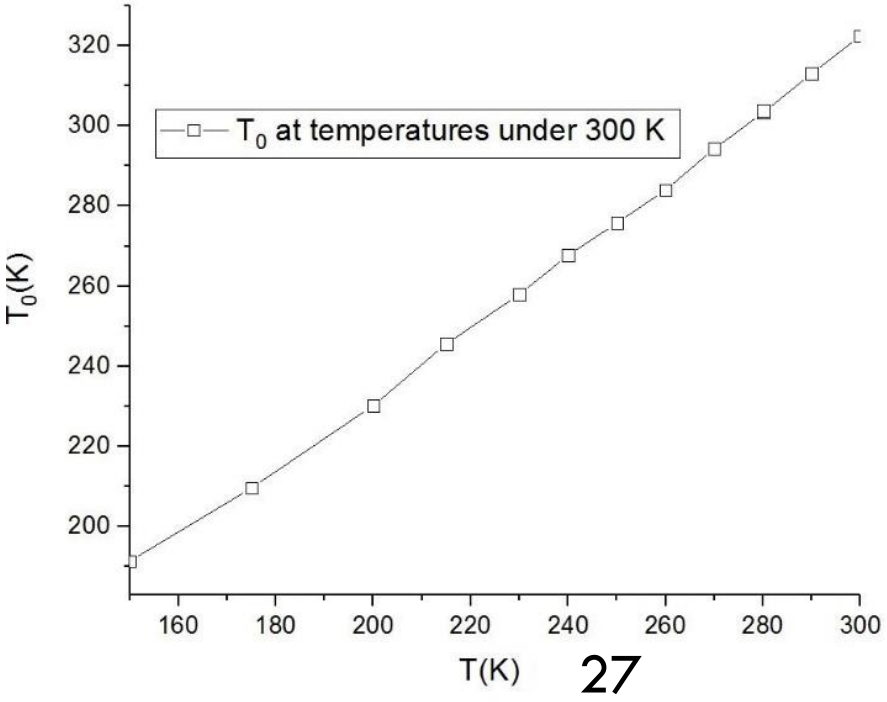
Subthreshold swing

$$S = \frac{2{,}3}{Slope(I_{Dst})}\frac{V}{Decade}$$



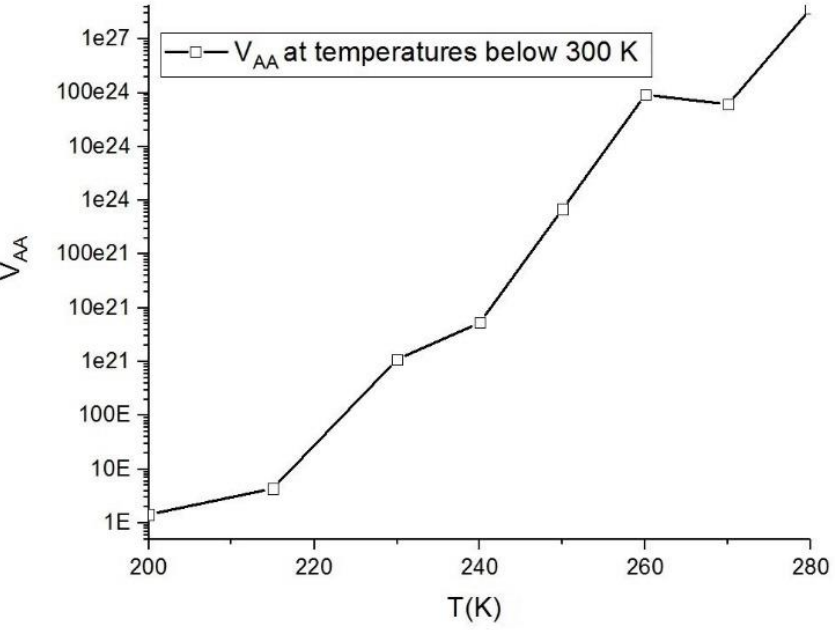
Characteristic temperature

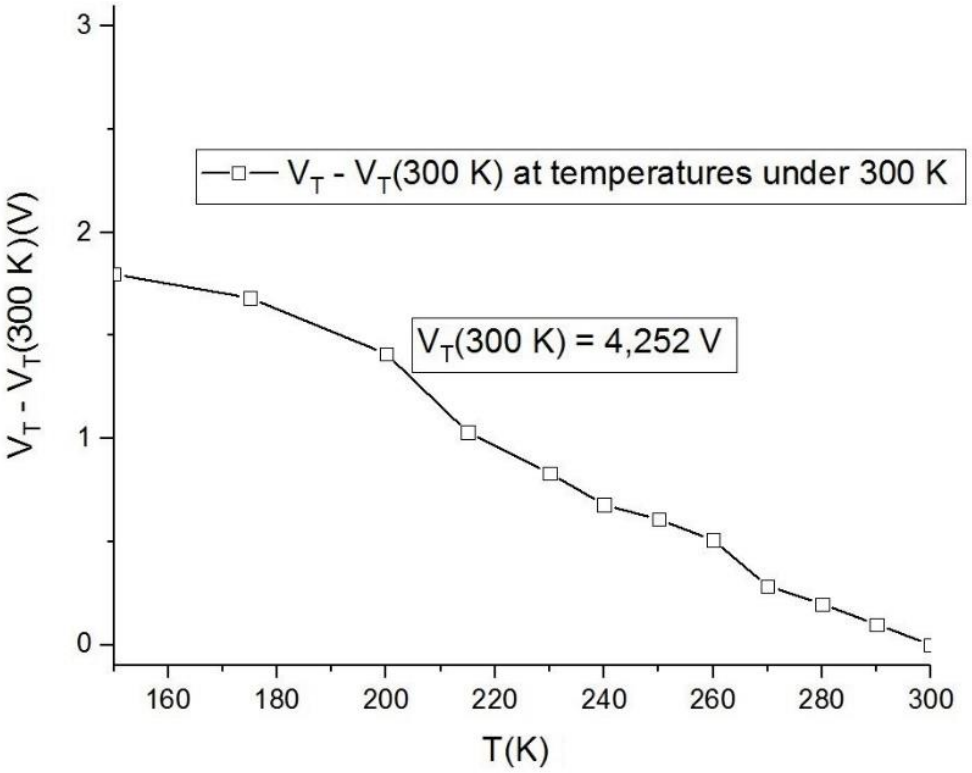
$$T_0 = T(\frac{\gamma}{2} + 1)$$



Results: Parameters extracted

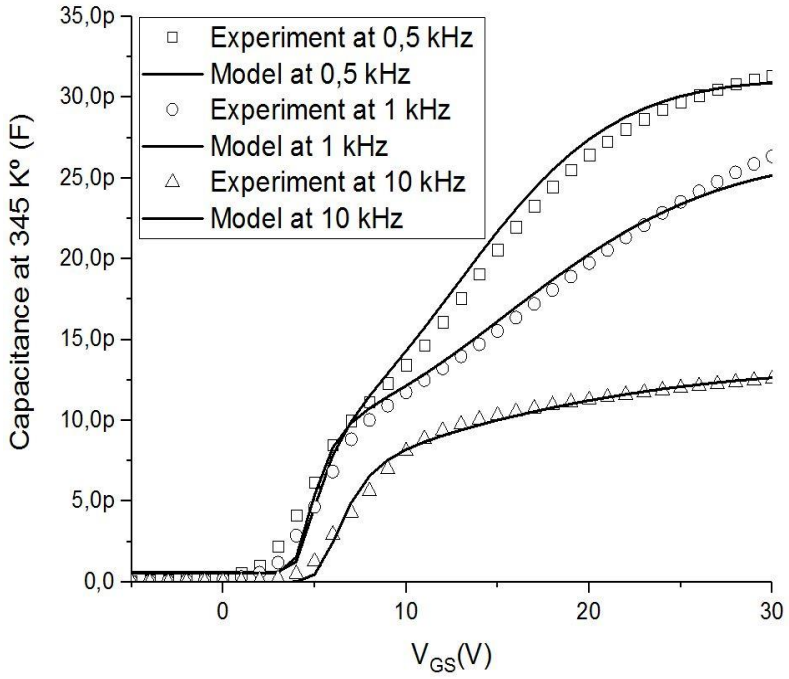
V_{AA} parameter





Threshold Voltage

Results: total gate capacitances



Capacitance vs Gate-Source Voltage at 500 Hz, 1 kHz and 10 kHz at 345 K

$$Q_{CH} = \frac{-WC_i^2}{I_{DS}}\mu_{FET}\frac{(V_{GTe} - V_{DSe})^{3+\gamma} - V_{GTe}^{3+\gamma}}{3+\gamma}$$

$$C_{TOT} = [|C_{EQ}|\frac{1-tanh(\beta)}{2}] + [|C_{GG}|\frac{1+tanh(\beta)}{2}]$$

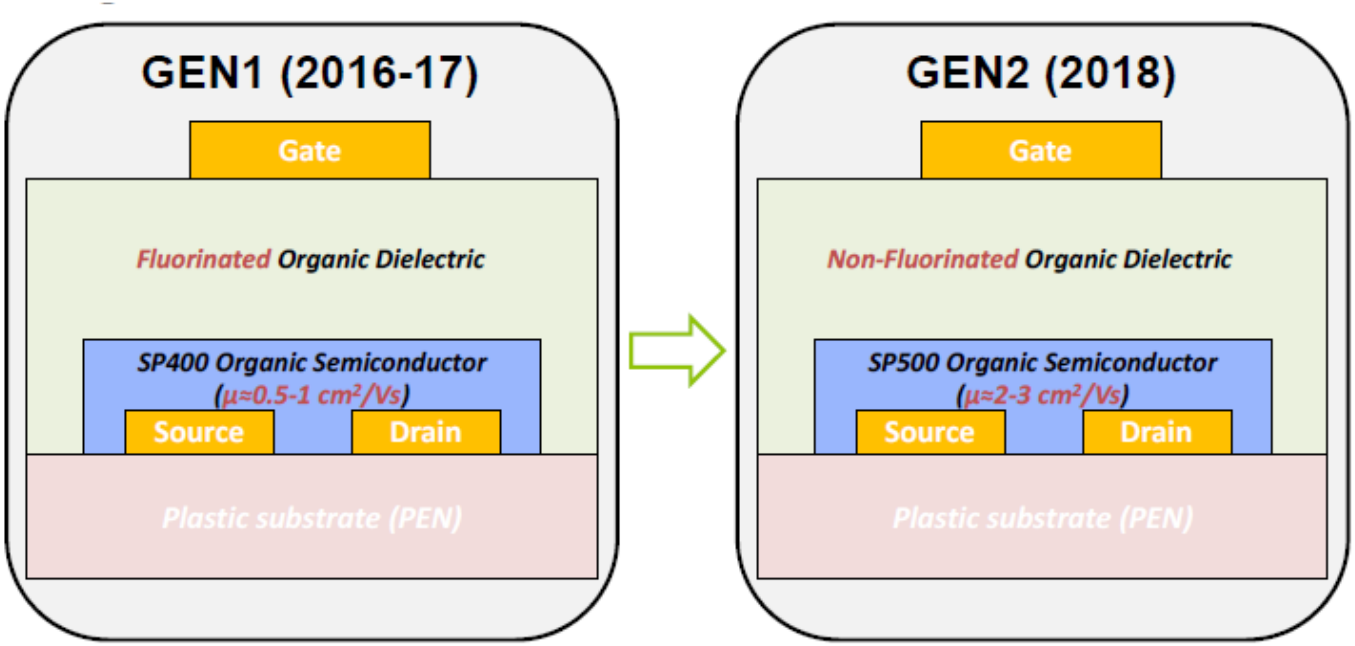
$$C_{CH-G} = -\frac{\partial Q_{CH}}{\partial V_{GS}} = \frac{\partial Q_G}{\partial V_{GS}} = -C_{GG}$$

$$C_{EQ} = \begin{cases} \dfrac{C_D CiWL}{(C_D + Ci)(WL)} & \text{if } V_{GS} < V_T \\ CiWL & \text{if } V_{GS} \geq V_T \end{cases}$$

$$C_D = \frac{\varepsilon_S LW}{W_D}$$

$$\varepsilon_i = \varepsilon_{i\infty} + \frac{\varepsilon_{i0}\varepsilon_{i\infty}}{1 + (\frac{w}{2\pi\eta})^{1.78p}}$$

Second OTFT technology



Measurements

- Linear regimen

$V_D = -1$ $V_G = 10V\ to\ 20V$ $steps: 0.1\ V$

- Saturation regimen

$V_D = -20$ $V_G = 10V\ to\ -20V$ $steps: 0.1\ V$

- Output characteristics

$V_D = 0\ to\ -20V$ $steps: 0.1\ V$

$V_G = -20V\ , -15V,\ -10V, -5V,\ 0V$

- Temperatures

$T = 350K, 325K, 300K, 275K, 250K, 225K, 200K, 175K, 150K, 125K$

Results: DC characteristics

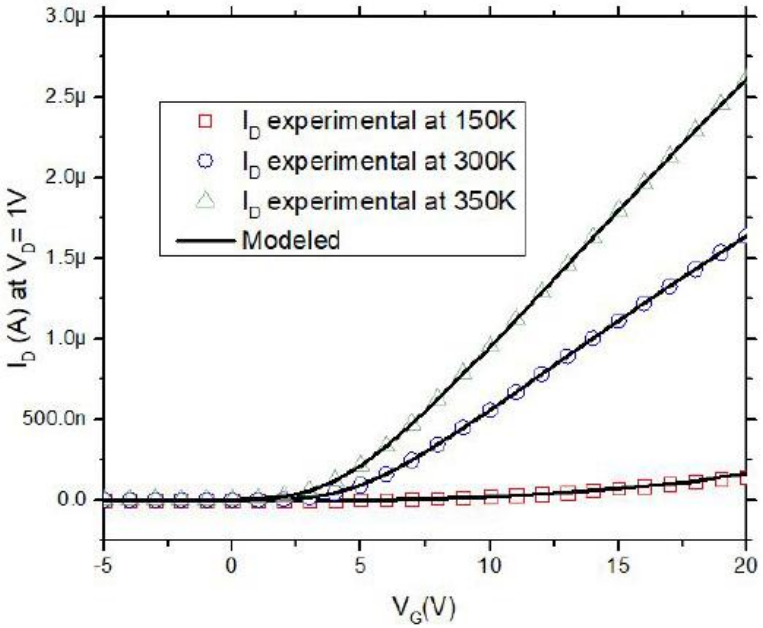
W/L =1000/80 μm

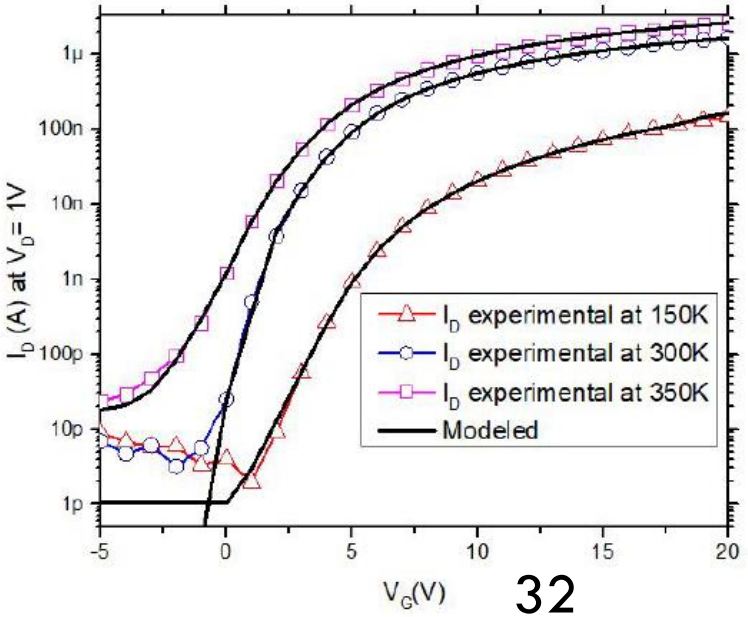
- Dielectric

$$d_i = 600\ nm \qquad \varepsilon_{ir} \cong 3$$

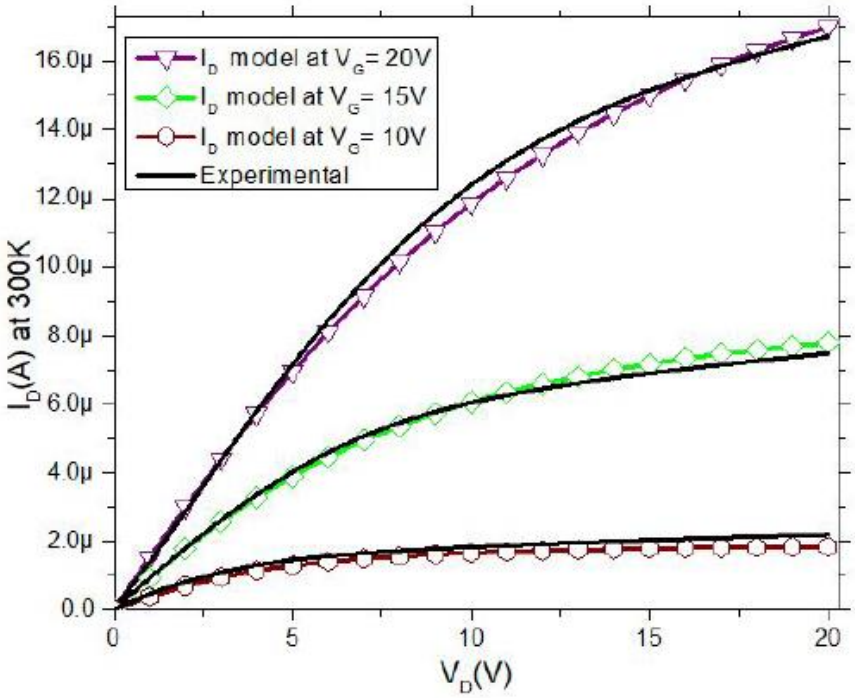
- Semiconductor

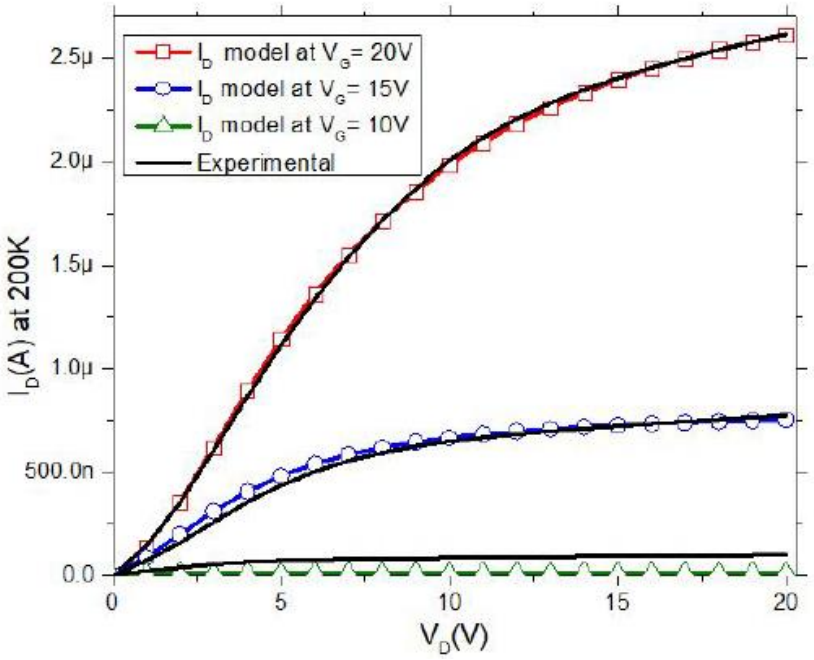
$$d_s = 40\ nm$$





Results: DC characteristics

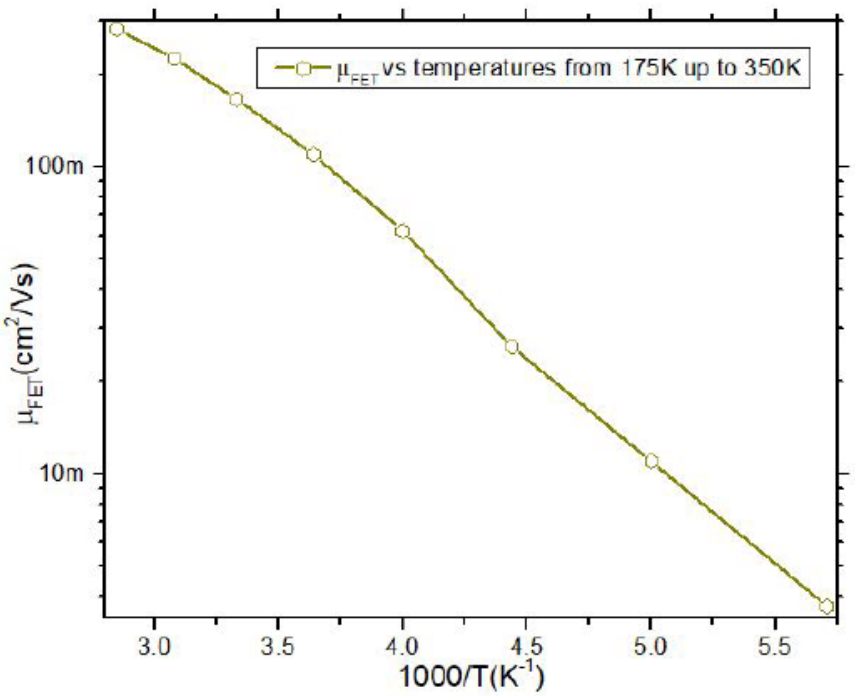


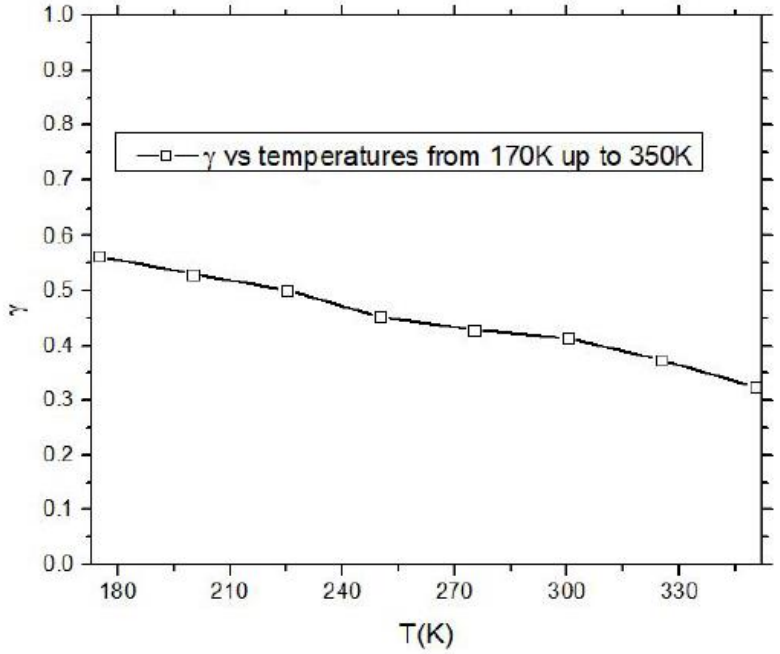


Results: Parameters extracted

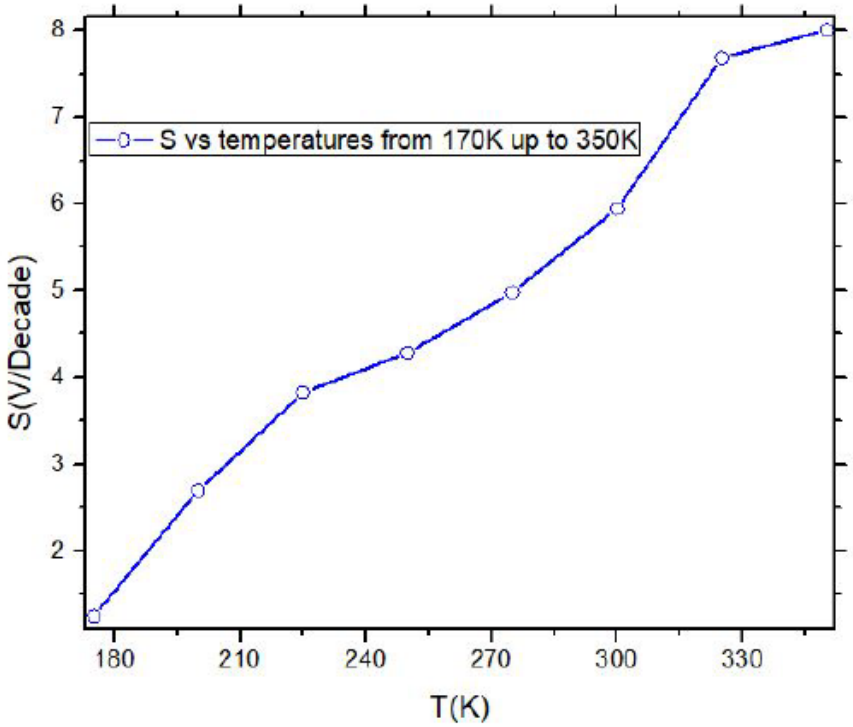
$UMEM$	$175K$	$250K$	$300K$	$325K$	$350K$
γ	0.5636	0.452	0.0.414	0.374	0.325
$S[V/Decade]$	1.251	4.285	5.946	7.683	8.006
$\mu_{FET}[cm^2/Vs]$	0.0037	0.062	0.167	0.226	0.282
V_T	7.22	4.351	2.747	1.821	0.985
$E_A[eV]$	0.019	0.026	0.031	0.033	0.035
$T_0[K]$	224.26	306.5	362.1	385.77	406.87

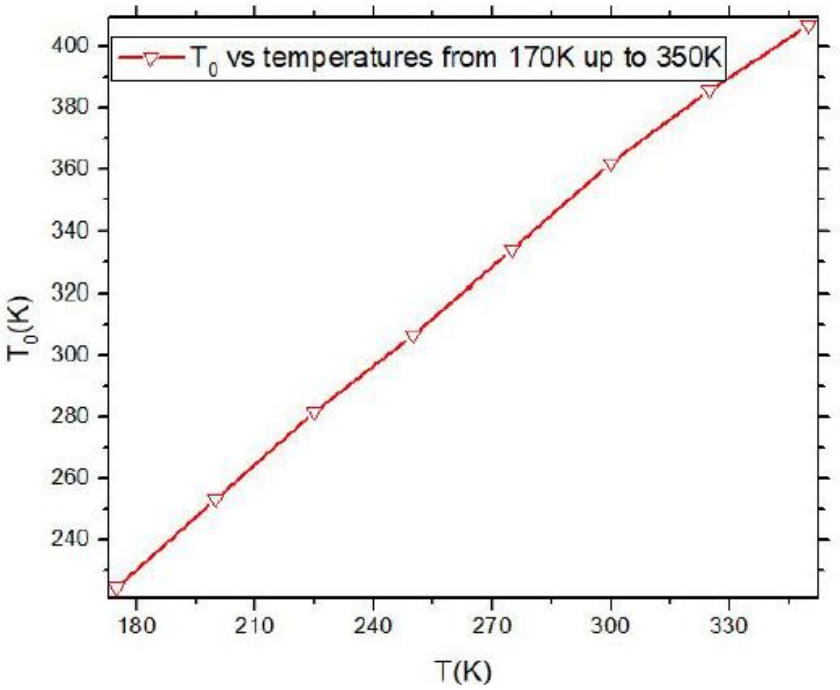
Results: Parameters extracted



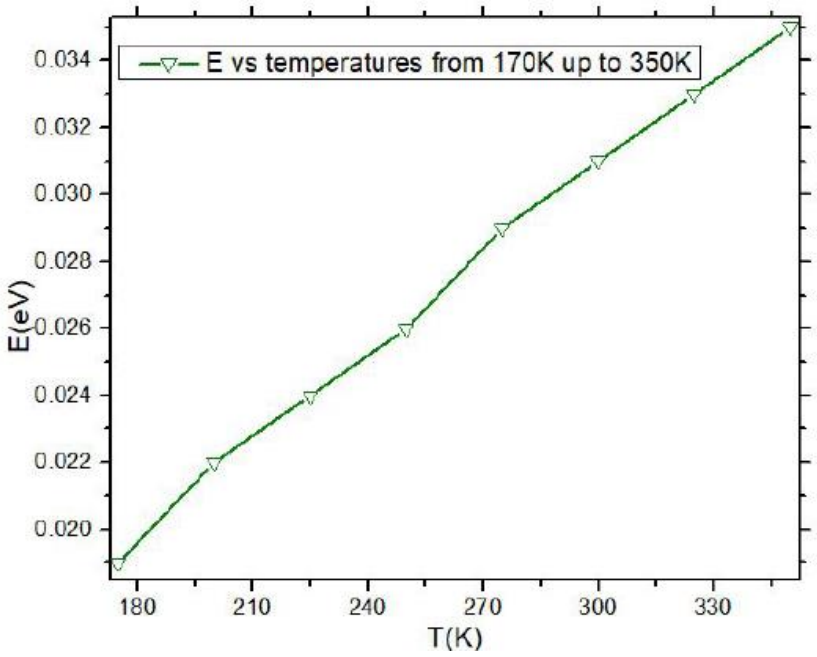


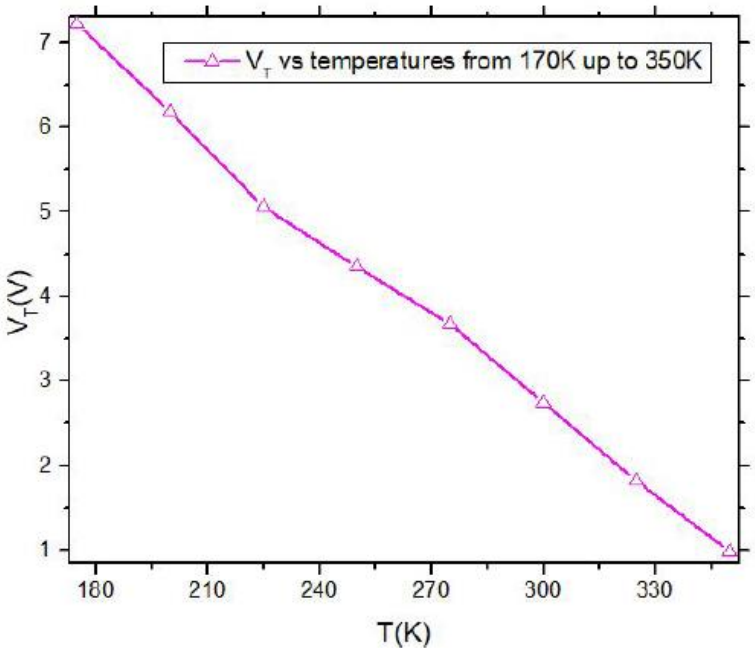
Results: Parameters extracted





Results: Parameters extracted



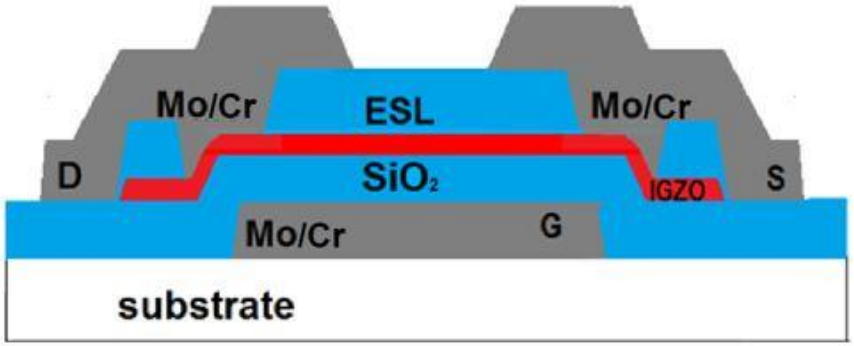


Results

- Contrary to most assumptions, T_0 increases with increasing temperature. The explanation of this phenomenon seems to be the same as for the increase of the characteristic energy of the tail DOS with T observed in a-Si:H materials from measurements of the optical absorption coefficient increase of the dynamic phonon disorder.

Cody,GDet al. (1981). “Disorder and the optical-absorption edge of hydrogenated amorphous silicon”. In: Physical Review Letters 47.20. doi:10 . 1103 / PhysRevLett . 47 . 1480, p. 1480.

IGZO TFT under study



- **Features of the device under analysis:**
- IGZO TNO
- Etch Stop Layer (ESL)
- $L = 20\ \mu m$
- $W = 100\ \mu m$
- Dielectric

  $d_i = 200\ nm \qquad \varepsilon_{ir} = 4.7$
- Semiconductor

  $d_s = 100\ nm$

Applied voltage and temperature ranges

- Transfer characteristics

$$V_G = -2V \;\; 10 \qquad V_D = \begin{cases} V_{D_{lin}} = 0.5V \\ V_{D_{sat}} = 10V \end{cases}$$

- Output characteristics

$$V_D = -1V \; to \; 10V \qquad V_G = \begin{cases} V_{G1} = 0V \\ V_{G2} = 4V \\ V_{G3} = 8V \\ V_{G4} = 10V \end{cases}$$

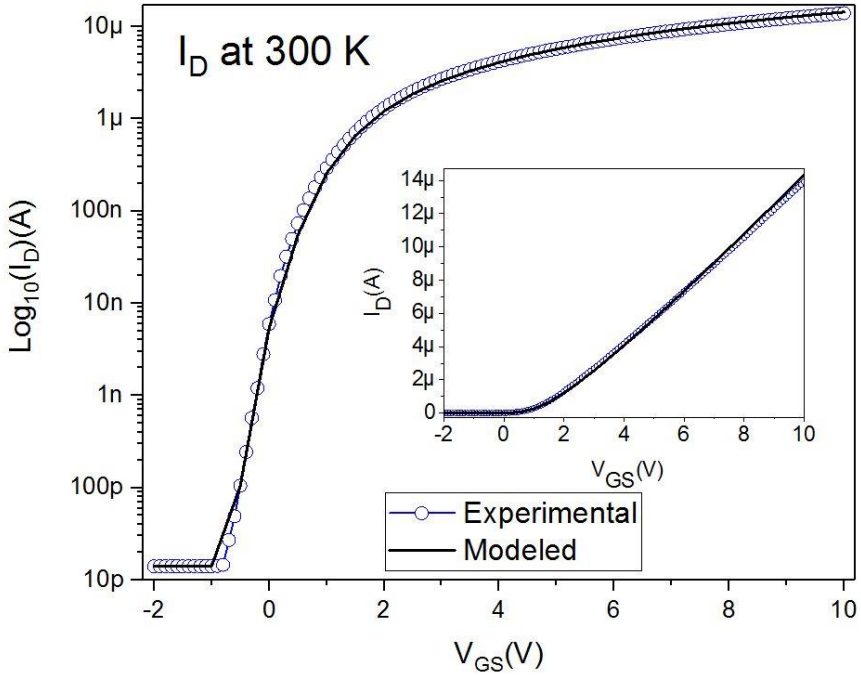
- Temperatures

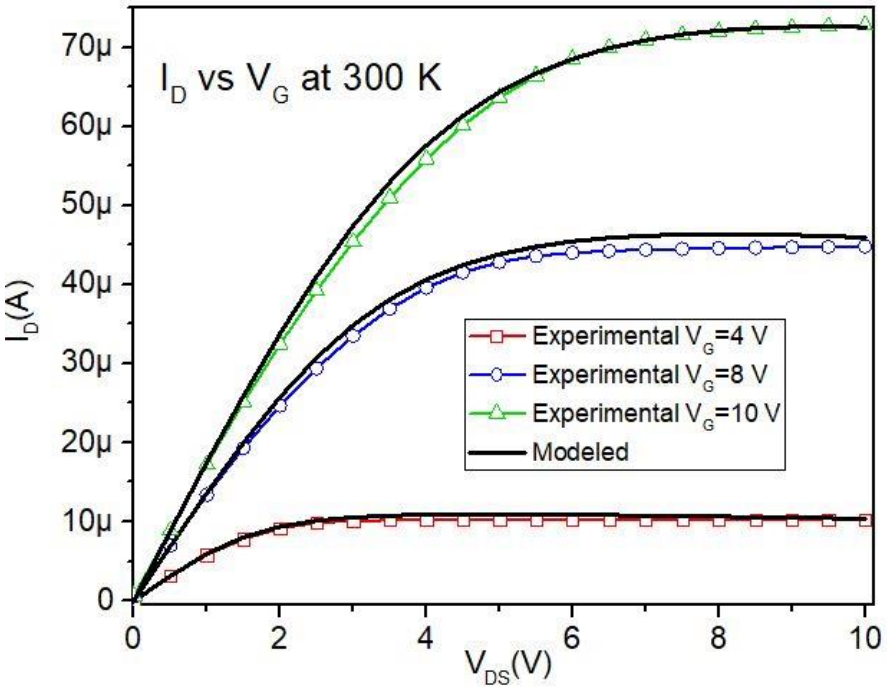
$$T = 210K \; to \; 370K$$

Results: DC characteristics

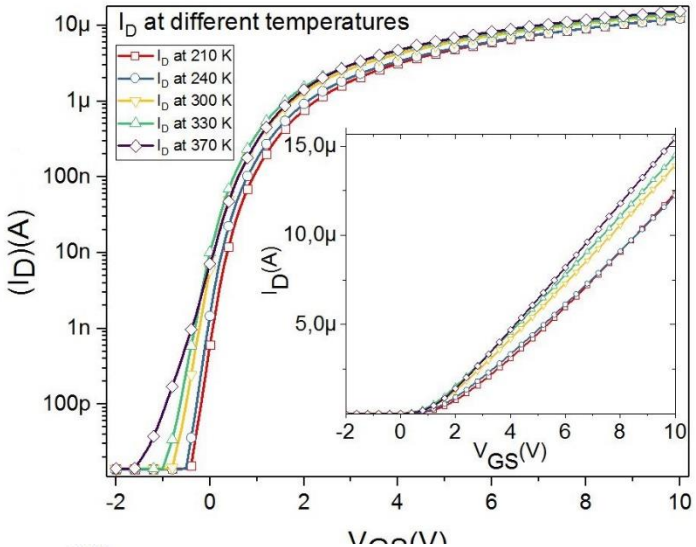
$$I_{DSb} = I_{DSo} \cdot \exp\left(-2.3\frac{(V_{GS} - V_T)}{S}\right)$$

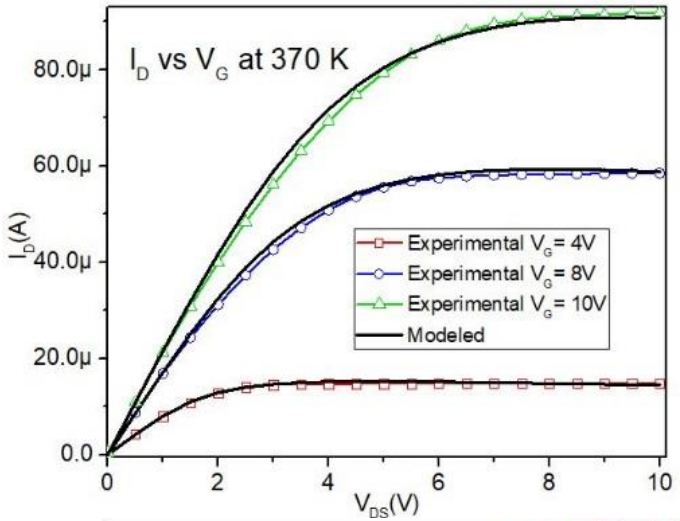
$$I_{DS} = \frac{W}{L} \cdot C_i \cdot \mu_{FET} \cdot \frac{(V_{GS} - V_T) \cdot V_{DS} \cdot (1 + \lambda \cdot V_{DS})}{\left[1 + R \cdot \frac{W}{L} \cdot C_i \cdot \mu_{FET} \cdot (V_{GS} - V_T)\right] \cdot \left[1 + \left[\frac{V_{DS}}{\alpha_S \cdot (V_{GS} - V_T)}\right]^m\right]^{\frac{1}{m}}}$$

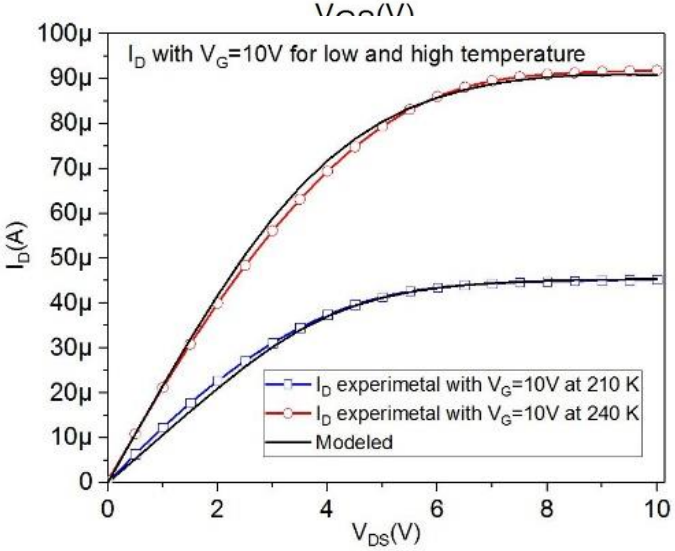


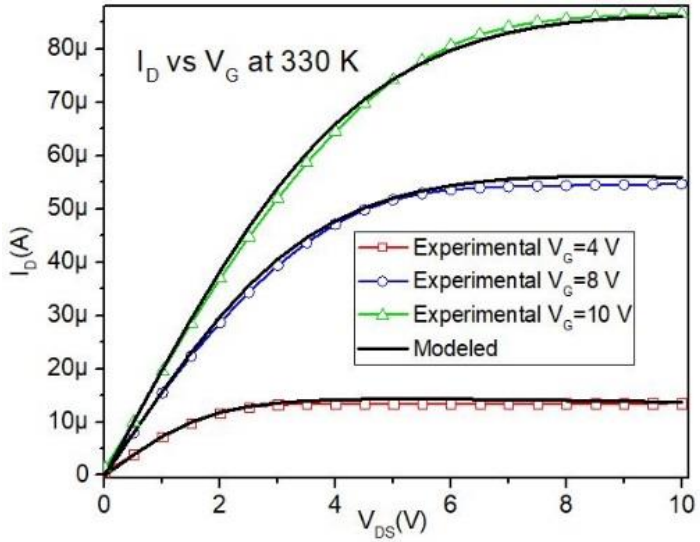


Results: DC characteristics



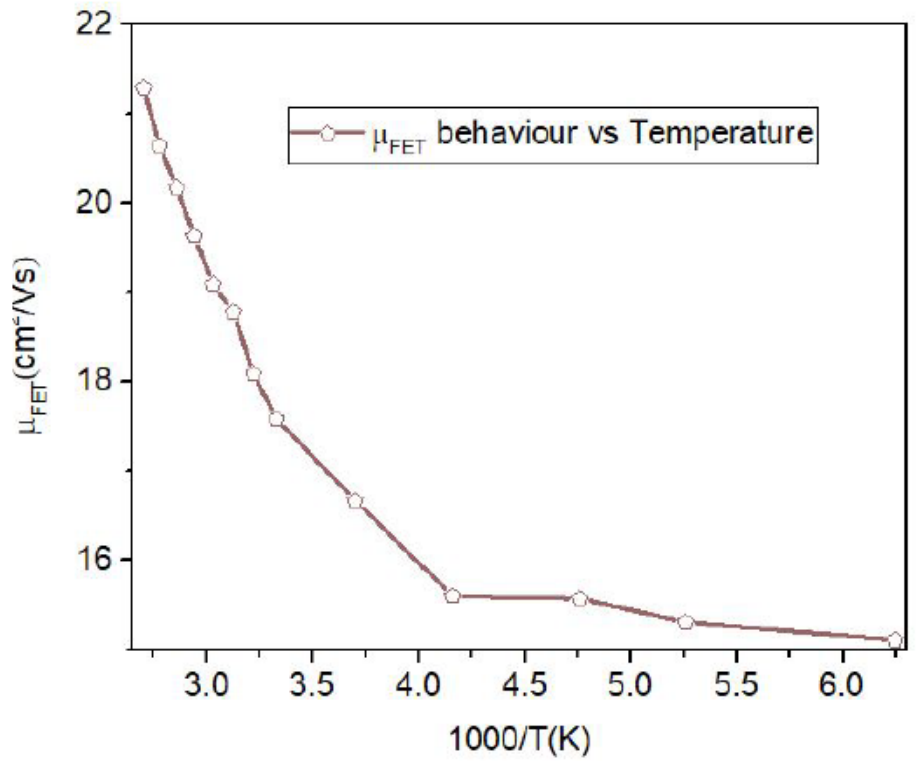


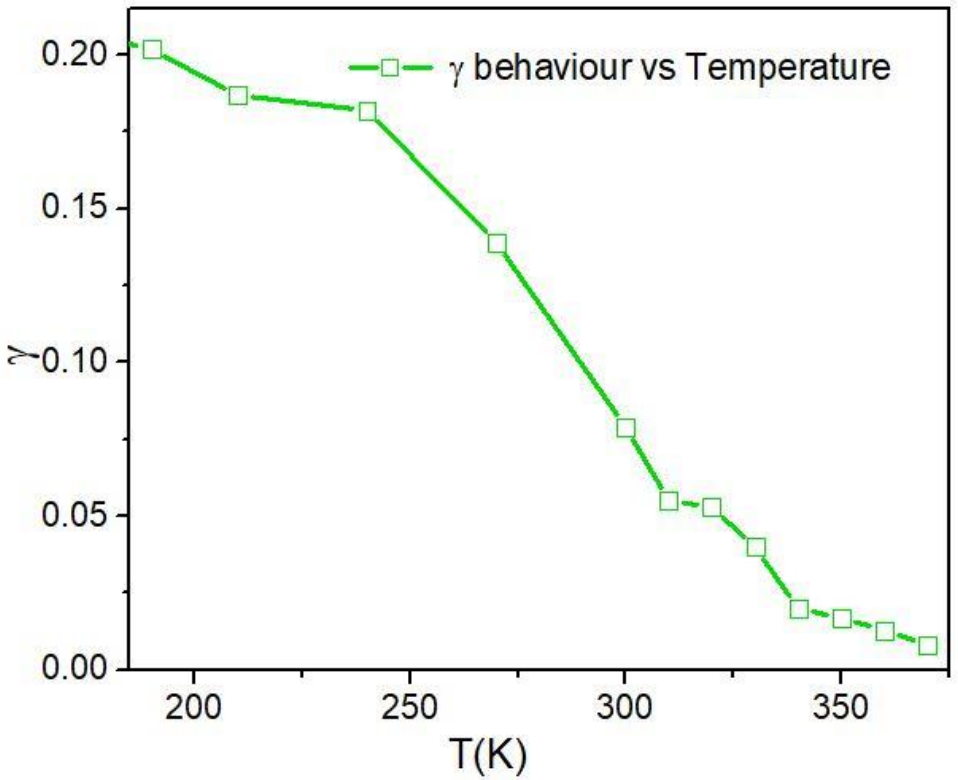




Results: Parameters extracted

γ *close to* 0 →crystalline-like behaviour





$V_{GS} = 10\ V$

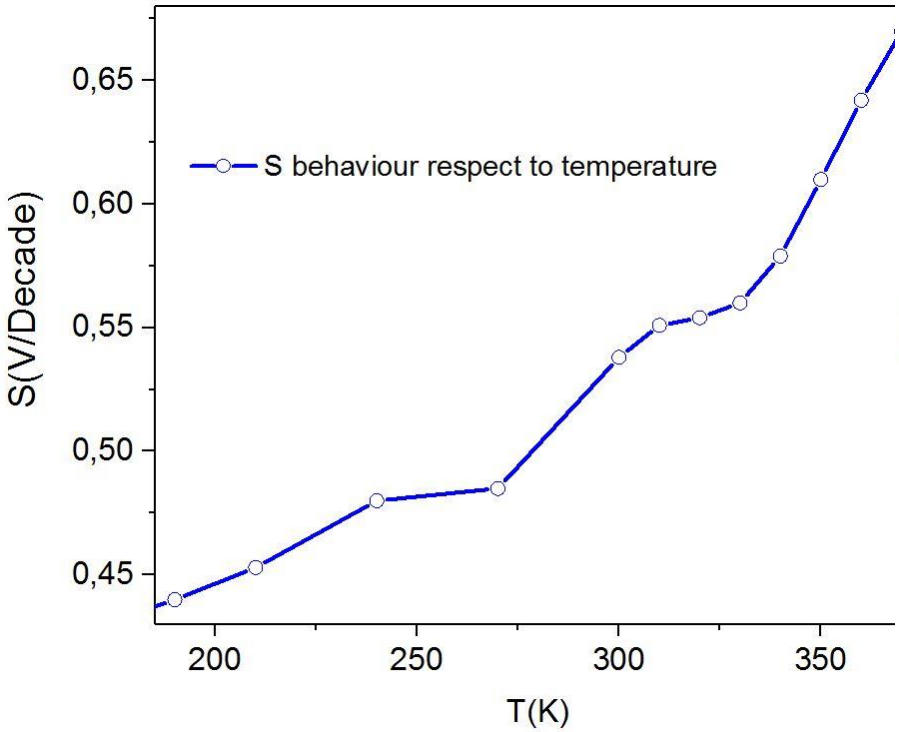
$$\mu_{FET} = \frac{\mu_O}{V_{AA}^{\gamma}} \cdot (V_{GS} - V_T)^{\gamma}$$

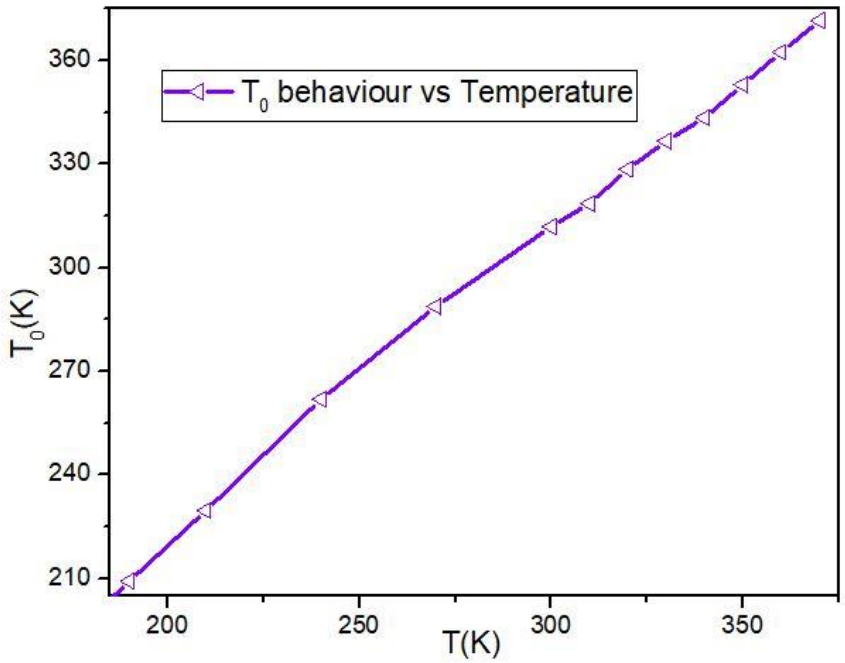
Results: Parameters extracted

Subthreshold swing

$$S = \frac{2{,}3}{Slope(I_{Dst})}\frac{V}{Decade}$$

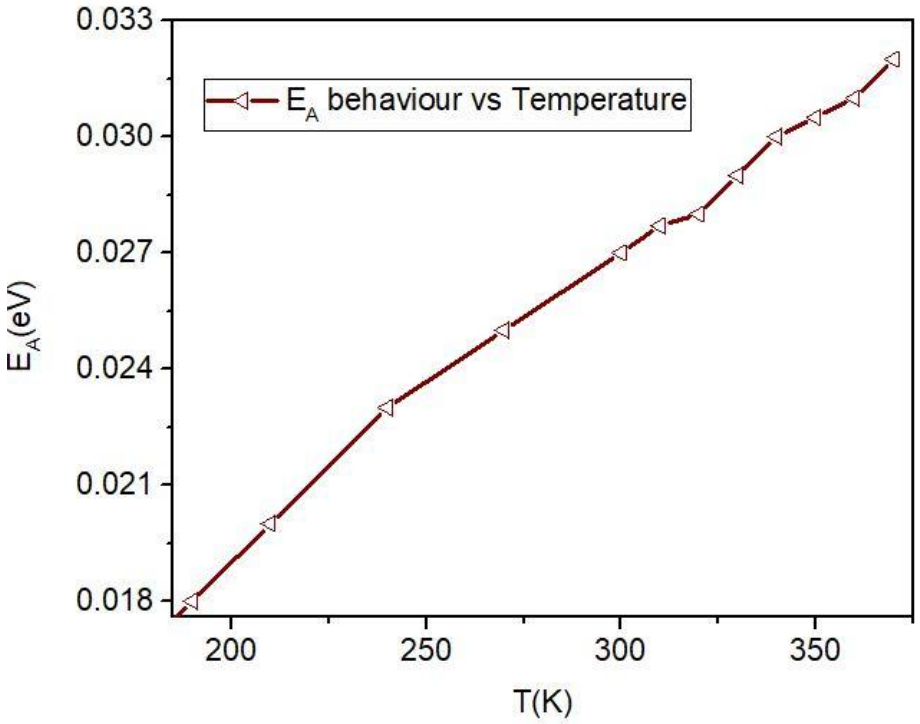
$$T_0 = T(\frac{\gamma}{2} + 1)$$



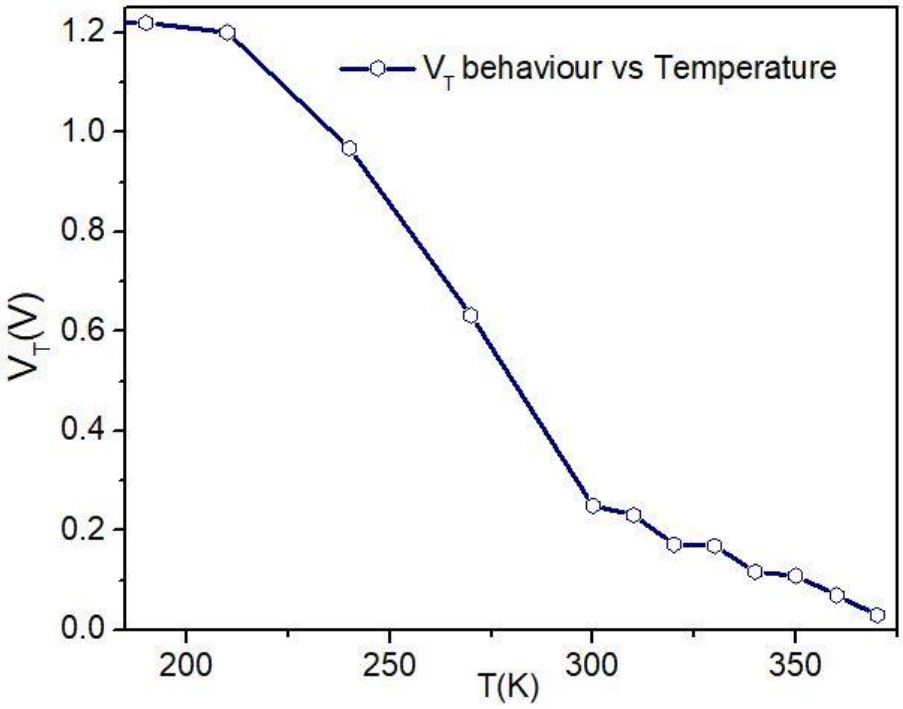


Results: Parameters extracted

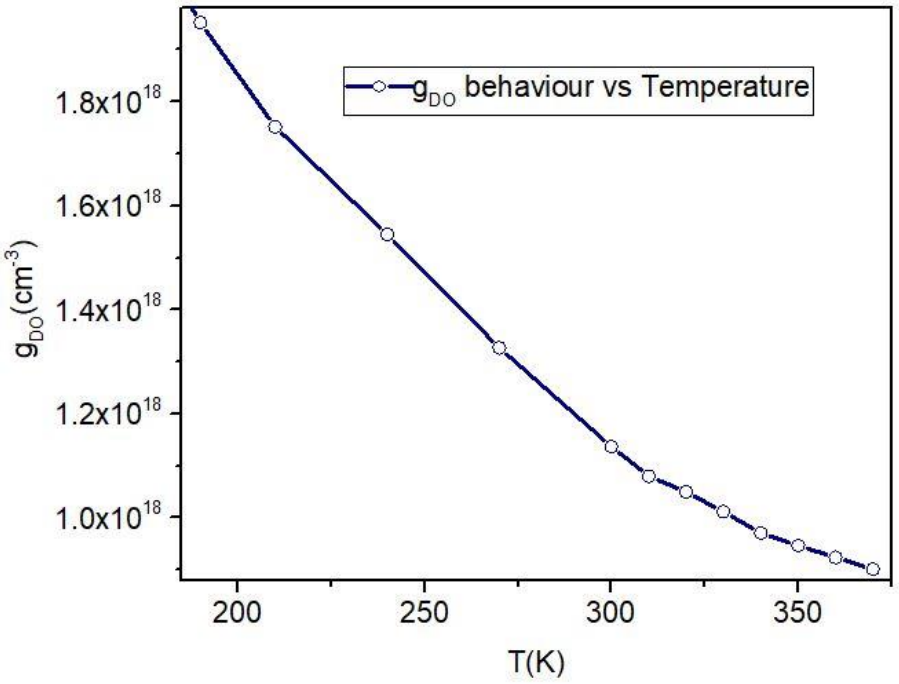
Activation Energy



Threshold Voltage



Results: Parameters extracted



$$g_{d0} = \frac{N_C \frac{2}{\sqrt{\pi}}\left(\left(\int_0^{\infty} \frac{\sqrt{x}}{1+e^{x-\frac{\varphi_s-\varphi_f}{\varphi_t}}} dx\right)\right)}{(kbT_T)\left(\left(\int_0^1 \frac{1}{1+Z\frac{T_T}{T}} dz.e^{\frac{\varphi_f}{kbT_0}}\right)\right)} \cdots$$

$$\cdots \frac{-\left(\int 0^{\infty} \frac{\sqrt{x}}{1+e^x} dx.e^{\frac{-\varphi_f}{kbT_0}}\right)}{-\left(\int 0^{\frac{\varphi_f-\varphi_s}{e\varphi_{TT}}} \frac{1}{1+Z\frac{T_T}{T}} dz.e^{\frac{\varphi_f}{kbT_T}}\right)}$$

Tail trap density at E_C

Results: Parameters extracted

	210K	270K	300K	350K	370K
γ	0.187	0.139	0.079	0.017	0.008
$\mu_{FET}(cm^2/Vs)$	15.57	16.67	17.58	20.174	21.29
$V_T(V)$	1.201	0.632	0.25	0.109	0.03
$S(V/Decade)$	0.196	0.211	0.234	0.265	0.291
$T_0(K)$	229.63	288.76	311.85	352.97	371.48
$E_A(eV)$	0.02	0.025	0.027	0.0305	0.032
$g_{ato}(cm^{-3})x10^{18}$	1.752	1.327	1.137	0.947	0.901
$D_{it}(cm^{-2}eV^{-1})$			$1.307x10^{11}$		

Noise in OTFTs

Mc Whorter Model ΔN	Hooge Model Δμ	Ghibaudo Model Δμ-ΔN
$\frac{S_{ID}}{I_D^2} = \frac{k^*}{f} \frac{1}{C_{ox}^2 WL} \frac{1}{(V_{GS} - V_{th})^2}$	$\frac{S_{ID}}{I_D^2} = \frac{q}{C_{ox} WL} \frac{\alpha_H}{f} \frac{1}{(V_{GS} - V_{th})}$	$\frac{S_{ID}(f)}{I_D^2} = \left[1 \pm \alpha_s \mu_{eff} C_i \frac{I_D}{g_m}\right]^2 \left[\frac{g_m}{I_D}\right]^2 S_{V_{FB}}(f)$

Slopes

m = -2

m =-1

Proportionality

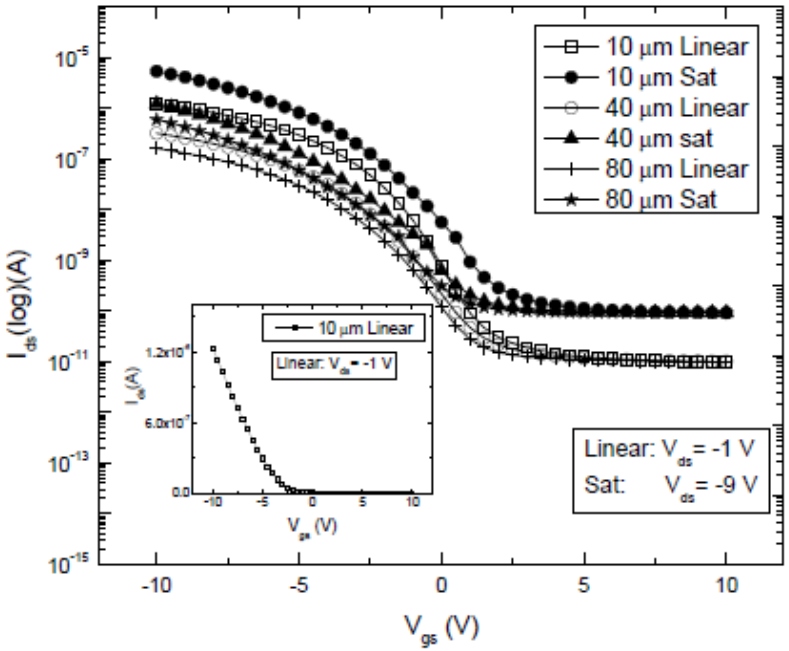
f^{-1}

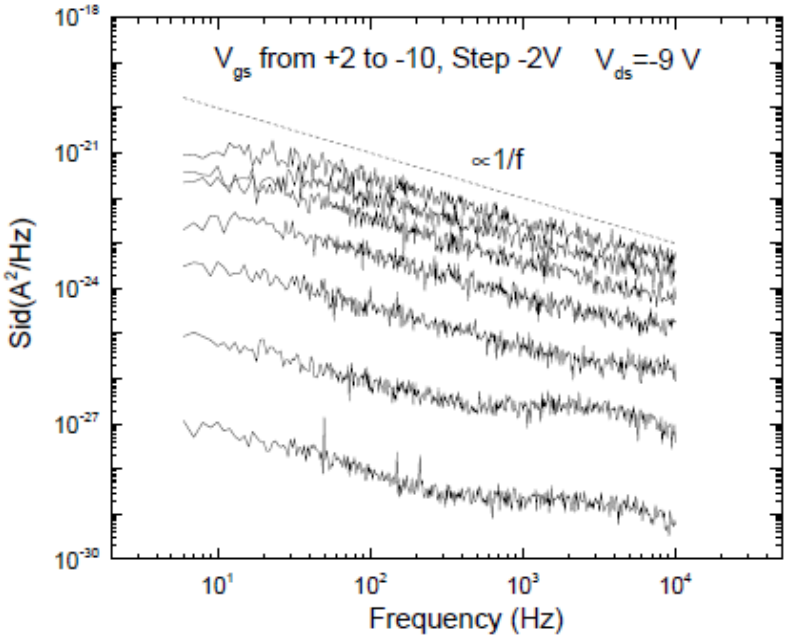
m = -1

Scalability

- ↑ L ↓ S_{ID}
- ↑ V_G ↓ S_{ID}

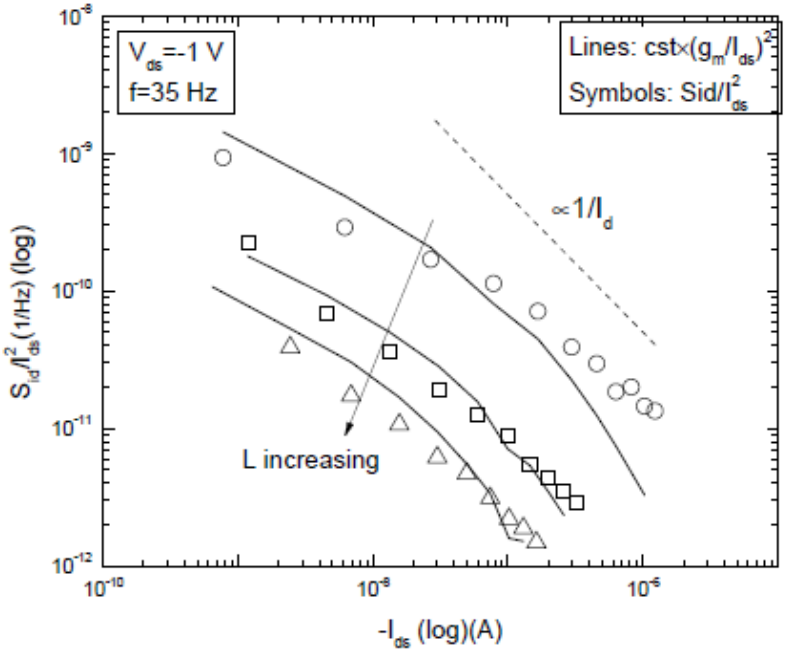
Noise in OTFTs

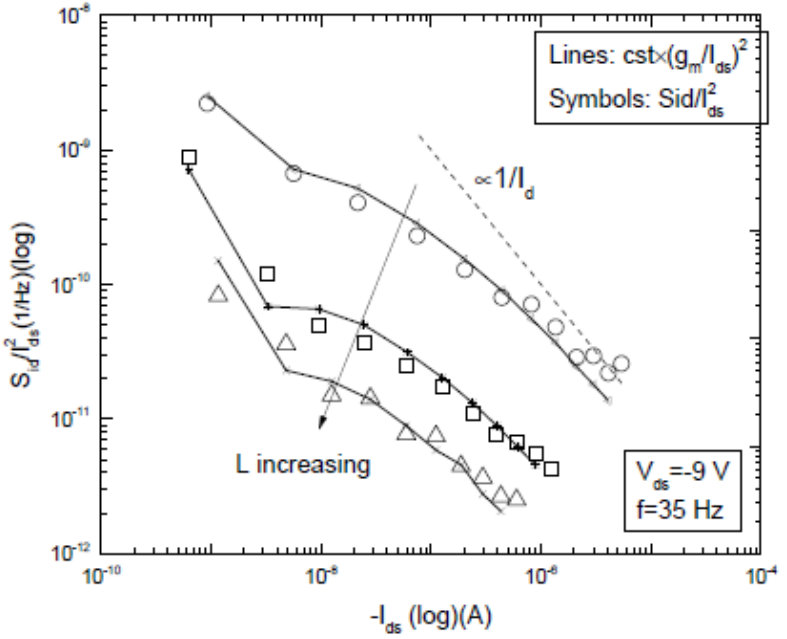




Noise in OTFTs

L=10μm





Conclusions

- Physically-based analytical models for OTFT and IGZO TFTs have been described
- They are both based on a single exponential DOS. This leads to the same type of equations for the drain current.
- Model parameters can be extracted by direct techniques: Unified Model and Extraction Method adapted to OTFTs and IGZO TFTs
- Models are validated by comparison with experimental data from 150K to 350K.
- Reasonable good agreement between the modeled and experimental data over range of temperatures.
- Threshold voltage decreases with increasing the temperature.
- The characteristic temperature and the field effect mobility increase as temperature is risen.

Conclusions

- The effect of the non-linear source and drain contacts is relevant at lower temperatures.
- The subthreshold swing increases as temperature is risen.
- The drain current increases with increasing the temperature due to the higher field effect mobility
- At high temperatures the OTFT and IGZO TFT behavior become closer to crystalline devices.
- Measured current noise PSD indicates a clear 1/f noise behavior over the explored low frequency range
- We concluded that the low frequency in the targeted devices is originated from the carrier number fluctuation due to trapping/release of charge carrier by trap states uniformly distributed beneath the entire gate area.

Acknowledgements

TNO innovation for life

Cinvestav

liten
cea tech

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Questions

Thank You